

THERMAL PERFORMANCE TESTING OF CRYOGENIC PIPING SYSTEMS

J. E. FESMIRE, NASA, Kennedy Space Center, Florida
S. D. AUGUSTYNOWICZ, Dynacs Inc., Kennedy Space Center, Florida
Z. F. NAGY, Dynacs Inc., Kennedy Space Center, Florida

ABSTRACT

Thermal performance measurement of piping systems under actual field conditions is important for space launch development and commercial industry. Knowledge of the true insulating effectiveness is needed in system design, development, and research activities. A new 18-meter-long test apparatus for cryogenic pipelines has been developed. Three different pipelines, rigid or flexible, can be tested simultaneously. Critical factors in heat leak measurements include eliminating heat transfer at end connections and obtaining proper liquid saturation condition. Effects due to variations in the external ambient conditions like wind, humidity, and solar radiation must be minimized. The static method of liquid nitrogen evaporation has been demonstrated, but the apparatus can be adapted for dynamic testing with cryogenics, chilled water, or other working fluids. This technology is suited for the development of an industry standard test apparatus and method. Examples of the heat transfer data from testing commercially available pipelines are given. Prototype pipelines are currently being tested and evaluated at the Cryogenics Test Laboratory of NASA Kennedy Space Center.

INTRODUCTION

In today's world, the use of cryogenics and low-temperature refrigeration is taking a more and more significant role. From food industry, transportation, energy, medical applications, to the International Space Station, cryogenic liquids must be stored, handled, and transferred from one point to the other. The basic problem for any application of cryogenics is protection against heat transfer so that the evaporation ratio will be as small as possible. This energy conservation translates into a lower cost of operation for the user. There are a number of scenarios of how to protect storage tanks and transfer lines from the heat. For example, for storage during a short period of time and the use of the cryogen to provide a source of gas, it is not necessary have a tank or piping system with an extremely low thermal conductivity factor. However, system process control is still important and the thermal insulation systems must be designed accordingly. On the other side is the application where long storage times and the quality of the liquid are of critical importance. Here we are looking for high performance materials that provide thermal isolation to the highest level that can be justified by design and economics [1]. Whatever the cryogenic application, it is obligatory to have the knowledge, from the heat transfer point of view, of how the system will operate. Without this knowledge, the end user will pay much more money than expected for life cycle operation of the system even though some initial savings were made by the selection of the lowest cost thermal insulation system.

With cryogenic use more prevalent and with the requirements for higher and higher energy efficiencies, the total system design in light of its heat load effects must be understood. The areas of process control with critical temperature requirements and the need for new hardware in developing areas such as high-temperature superconducting electrical devices will drive industry to manufacture more robust and efficient components. The understanding of small manufacturing changes and their effects on the final product can now be tested. Initial capital outlay can be reduced by sizing the system correctly instead of oversizing it as is often the case.

The Cryogenic Test Laboratory at the NASA Kennedy Space Center has developed a new Cryogenic Pipeline Test Apparatus for testing pipelines under different temperature, vacuum pressure and flow conditions. Up to three different pipelines, in lengths of 18 meters or longer, can be tested simultaneously. The apparatus gives accurate heat leakage data for the test article under simulated conditions of an actual field installation.

1 TEST APPARATUS

The cryogenic pipeline test apparatus includes two cold boxes, one upstream and one downstream, between which the test articles are connected. The method of testing can be static (boil-off) or dynamic (flow-through). Figure 1 gives a simplified schematic of the apparatus configured for the static method of testing. Cryogen, in this case liquid nitrogen, is delivered to the test apparatus from a 23 cubic meter storage tank at a fairly low pressure of approximately 70 kPa. The cryogen is supplied to the individual test pipelines (through a heat exchanger coil), the upstream cold box, and the downstream cold box. Overall views of the apparatus showing three different 18-meter-long cryogenic pipelines under test are shown in Figure 2. The cold boxes are generally oriented so that the downstream end of the pipeline is slightly elevated. The cold boxes are mobile such that the apparatus can be reconfigured for different test requirements and a variety of different test articles. All necessary instrumentation to run the test is also included. The data monitoring and recording system is based on Field Point hardware and Lab View software from National Instruments.

In fixed systems additional high point bleeds can be utilized to assure the complete filling of the pipelines. The cold boxes are filled with the test fluid for thermal conditioning. The pipeline test fluid is routed through a heat exchanger coil inside the upstream cold box to provide single-phase flow through the pipeline. The ends of each pipeline are connected to the cold boxes such that end effects (heat transfer along the axis of the pipeline) are minimized to an inconsequential level. The connections are made using a custom adapter flange that interfaces with the flexible metal bellows portion of the cold box. These adapter flange assemblies are fully quenched by the test fluid inside the cold boxes during operations. The contraction and expansion of different diameter pipelines are accommodated by flexible bellows assemblies on the cold boxes. In addition, the downstream cold box is mounted on wheels for accommodating the axial movements of the pipeline test articles. Flow control valves, mass flow meters, and temperature measurements are used to assure that a wide range of different test articles can be tested in a standardized way. Electric heater tapes wrapped around the outer surface of the pipelines are used to control the warm boundary temperature.

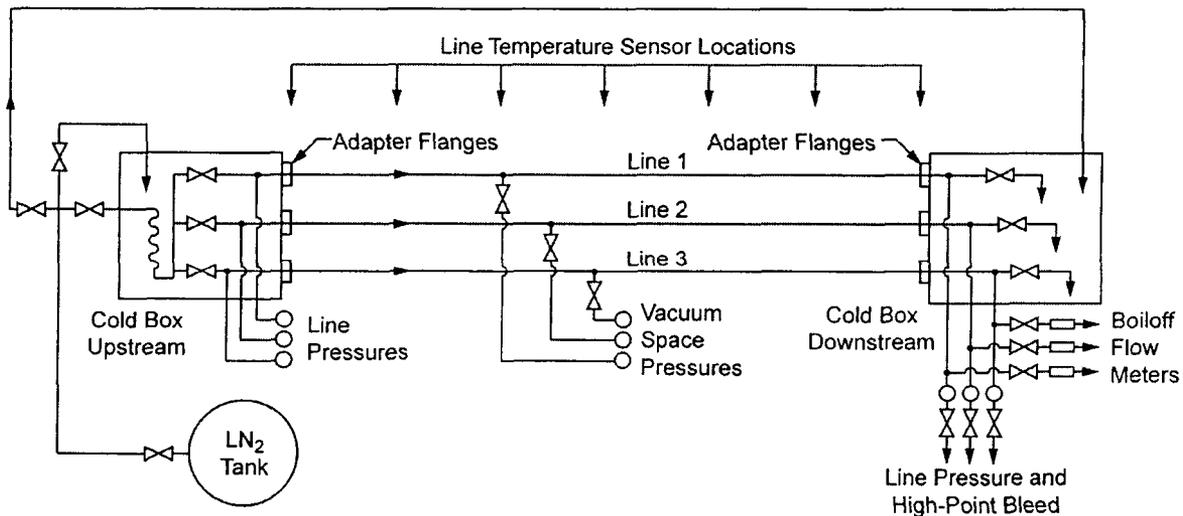


Figure 1: Simplified mechanical schematic of the cryogenic pipeline test apparatus.

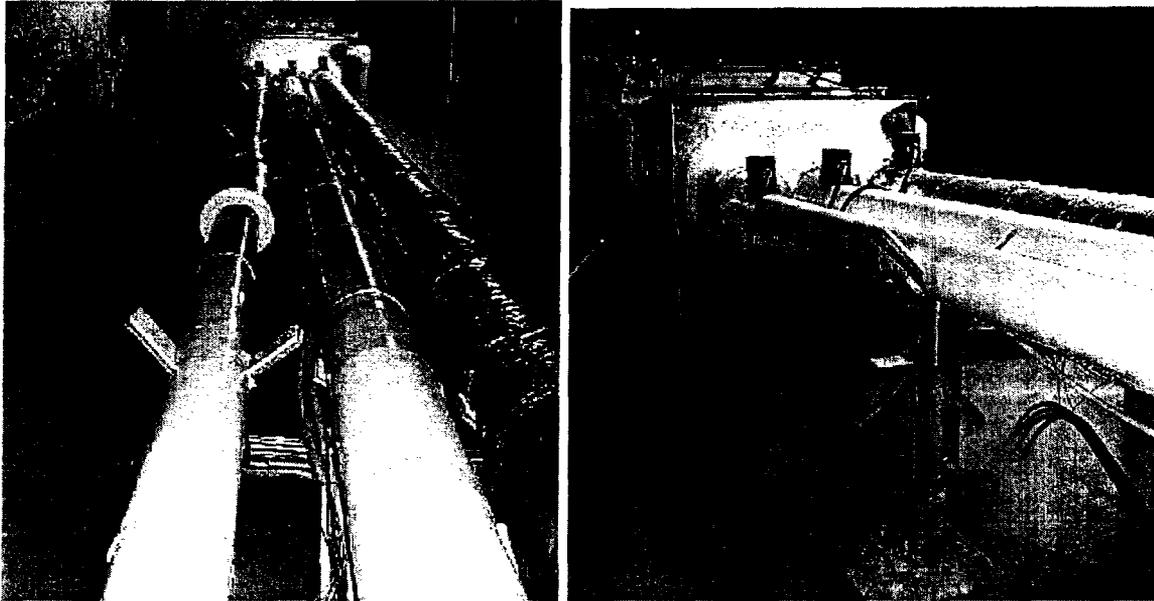


Figure 2: Views of the cryogenic pipeline test apparatus with three 18-meter-long test articles installed: the overall test set-up is shown on the left, the upstream cold box is shown on the right.

2 METHOD OF TESTING

The method of testing using the cryogenic pipeline apparatus can be static (boil-off) or dynamic (flow-through). The static method of liquid nitrogen evaporation, commonly referred to as the boil-off method, is described as follows. The test article, a piping system, component, or pipeline, is thermally conditioned prior to testing. The unit under test must be completely filled with liquid to ensure one hundred percent contact with the internal flow area of the test article. Failure to establish this condition will result in erroneous data or even no useful information at all. High point bleed valves located inside the downstream cold box are utilized to assure this complete filling. This liquid must be supplied at the saturated temperature condition that corresponds to the ambient pressure. If this liquid conditioning is not achieved, then the overall steady state condition will not be achieved during the evaporation or boil-off phase of the operation (that is, the boil-off flow of gas will be grossly inaccurate). To standardize boundary temperatures, heat is applied to the entire length of the test article. The warm boundary temperature is kept at approximately 310 K but can be adjusted higher or lower according to the specific test requirements. This standardization helps eliminate the effects of uneven temperature distributions and minimizes effects from variations in environmental conditions such as solar radiation, wind, or moisture.

For a typical test of a high performance pipeline, the system requires from 24 to 48 hours of thermal conditioning (cold soak) by maintaining a small replenish flow for liquid nitrogen through the line. After this time when all temperature sensors (from inside to outside and from end to end of the line) are verified to be steady and all heat transfer effects are stabilized, the main part of the test can begin. First, the pipeline inlet and outlet valves located inside the cold boxes are closed. The sequence and timing of the closing of these valves, as well as the associated high point bleed valves and the boil-off flow valves, has been found to be critical for obtaining a good steady-state boil-off result. The thermal performance of the test article is analyzed by continuous monitoring of all temperature and pressure distributions.

The heat leakage rate (watts) is computed from the boil-off mass flow rate and the latent heat of vaporization of the cryogen. The overall thermal performance factor, k_{oafi} , is then directly calculated from knowing the length, piping diameters, and boundary temperatures. The preferred units for the k_{oafi} are milliwatts per meter-kelvin (mW/m-K). The k_{oafi} , further described in the paper by Fesmire and Augustynowicz [2], is useful for comparing the performance of different size pipelines for actual field installations.

Another method of operation is the dynamic, flow-through type of test. The line flow rate and temperature difference from the inlet to the outlet are the key measurements in this case. This method can therefore be extended for use with other fluids such as chilled water or hot oil.

3 EXAMPLE TEST RESULTS

The heat leakage rate data from three tests of three different test articles are given as an example of the capability of the test apparatus and the method of the testing. The three test articles, all commercially available cryogenic piping products, were procured in three 6-meter long segments. The inside line size was approximately 30-mm diameter. These pipelines include polyurethane foam (line 1), vacuum-jacketed multilayer (VJ/MLI) with two bayonet joints (line 2), and VJ/MLI with two field joints (line 3).

The boundary temperatures were approximately 78 K and 310 K for all tests. The test data for the foam pipeline, Line 1, is summarized in Figures 3-5. Figure 3 gives the temperature profile while Figure 4 shows the line pressure variation with time. The heat transfer performance is given in Figure 5 with the boil-off gas flow rate and k_{ofi} profiles. The thermal performance in this case was determined to be approximately 21 mW/m-K at an 80 percent full condition. This value is in good agreement with other insulation test data for polyurethane foam in a like-new condition. Similar test data for the VJ/MLI lines is given in Figures 6-8. The thermal performance of Line 2 was determined to be approximately 0.8 mW/m-K while the value for Line 3 was determined to be approximately 0.7 mW/m-K. These values are reasonable for a multilayer insulation system of insulation under high vacuum condition when the effects of spacers and joints are included in the analysis.

The rate of heat leakage into the pipeline is calculated by equation 1. This heat leakage rate in watts (W) is the product of the volumetric flow rate, gas density, and heat of vaporization. The basic heat transfer relation for determining the overall thermal performance factor, k_{ofi} , is given by 2.

$$Q = V\rho h_{fg} \quad [\text{W}] \quad (1)$$

$$k_{\text{ofi}} = \frac{V\rho h_{fg} \ln\left(\frac{D_o}{D_i}\right)}{2\pi L\Delta T} \quad [\text{mW/m-K}] \quad (2)$$

The sources of error for the cryogenic pipeline test apparatus were analyzed. A summary of the errors is given in Table 1.

Table 1. Sources of error for the cryogenic pipeline test apparatus

Symbol	Description	Units	% Error
V	volumetric flow rate	sccm	1%
ρ	gas density	g/cm^3	0.72%
h_{fg}	heat of vaporization	J/g	2%
D_o and D_i	outer and inner diameters	m	0.11%
L	effective heat transfer length	m	0.14%
ΔT	delta temperature (WBT – CBT)	K	1.9%

The error introduced by each parameter is taken into account for the calculation of the total error. The "Error Analysis of Experiments" equation listed in *Perry's Chemical Engineers' Handbook* was used as the basis for the analysis [5]. The overall accuracy of the k_{ofi} is estimated to be 3.1% for a typical test scenario.

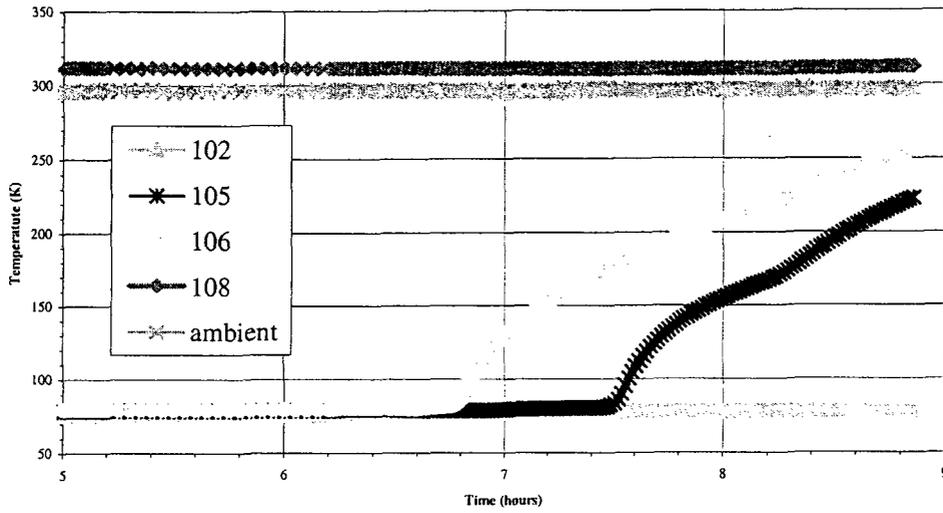


Figure 3: Temperature profile for the foam pipeline.

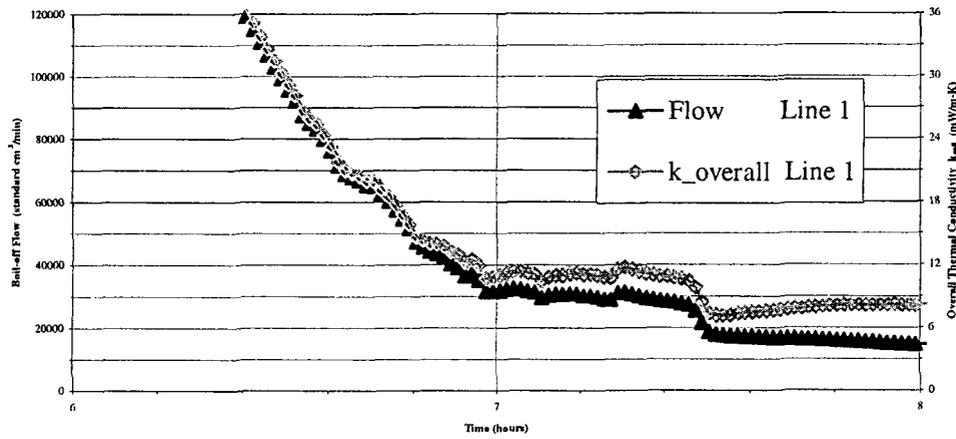


Figure 4: Line pressure profile for the foam pipeline.

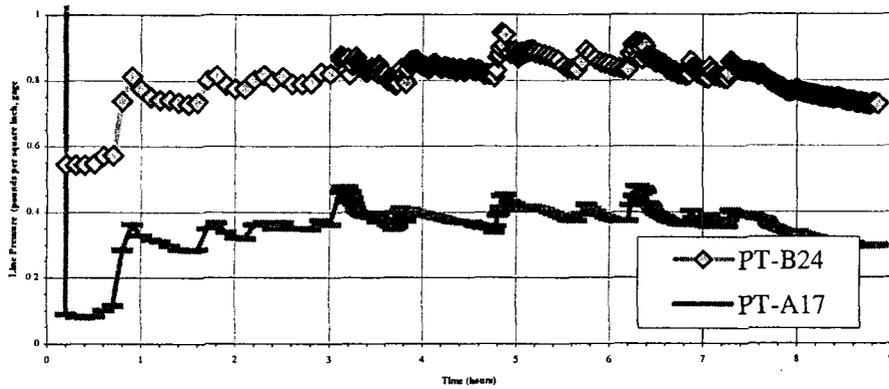


Figure 5: Boil-off flow rate and overall thermal conductivity profiles for the foam pipeline.

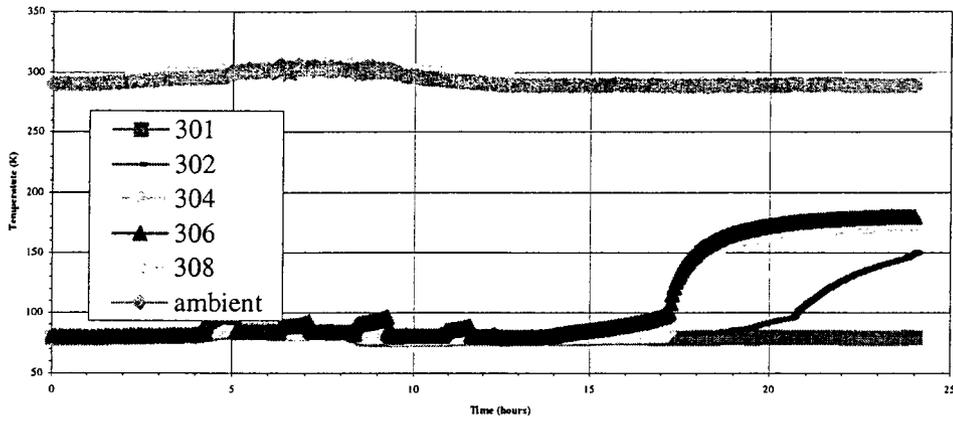


Figure 6: Temperature profile for the VJ/MLI (field joints) pipeline.

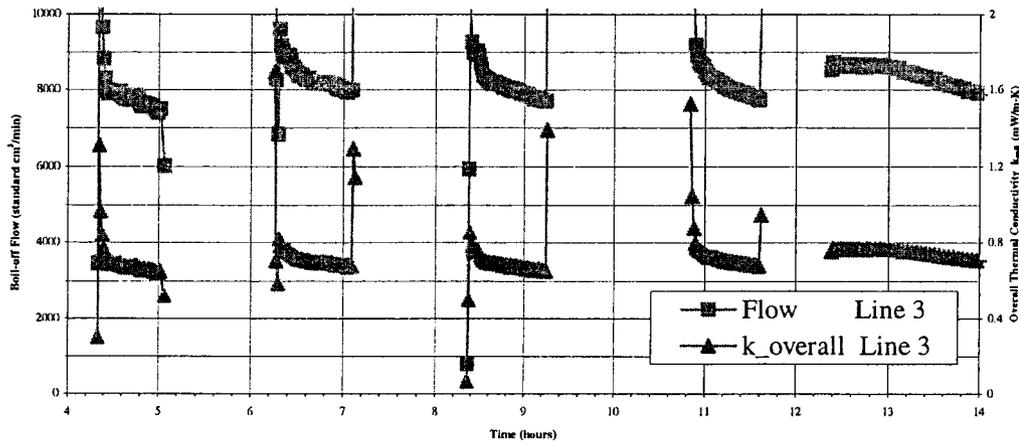


Figure 7: Boil-off flow rate and overall thermal conductivity profiles for the VJ/MLI (field joints) pipeline.

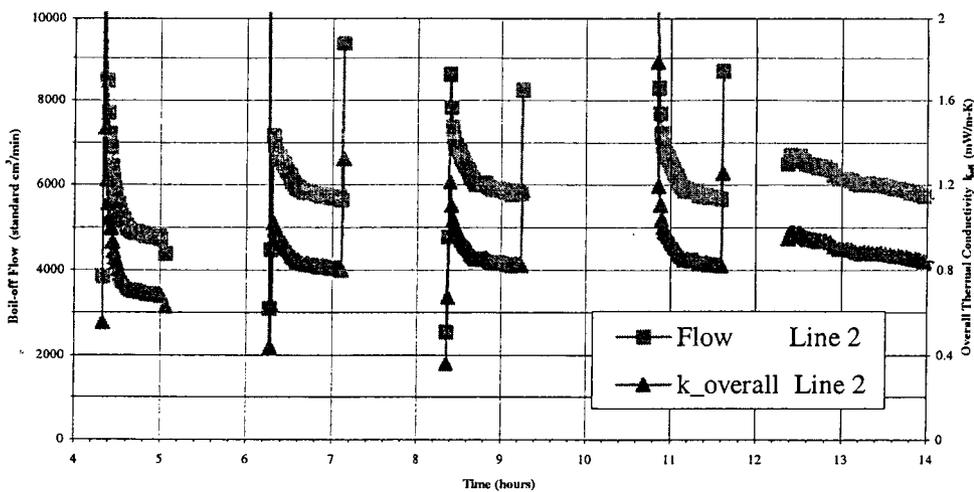


Figure 8: Boil-off flow rate and overall thermal conductivity profiles for the VJ/MLI (bayonets) pipeline.

4 APPLICATIONS OF PIPELINE TEST APPARATUS

The pipeline test apparatus and method of operation can provide the basis for a standardized test of the thermal performance of pipelines or piping systems. Existing standards such as ASTM-C-335, *Standard test method for steady-state heat transfer properties of horizontal pipe insulation*, have strict limitations such as applicability for system operating temperatures above ambient [4]. Other limitations may include small temperature differences such as 10 K or relatively high thermal conductivity values such as around 30 mW/m-K. To date cryogenic pipelines in the temperature range from 77K to 310K have been tested. The apparatus is readily adaptable for refrigeration temperatures of about 230 K up to process temperatures of about 373 K. The apparatus is also adaptable to valves, skid complexes, and other equipment in addition to pipelines of any length. Some important industrial applications may include transfer lines for liquefied natural gas or for warm crude oil beneath the sea. Other projects under consideration are high-temperature superconducting (HTS) power transmission lines that require cooling with liquid nitrogen.

The pipeline test apparatus at the Cryogenics Test Laboratory is US patent pending and currently slated for use in a number applied research projects supporting the development of energy efficient space launch sites. Preliminary work on the insulation envelopes for flexible HTS power cables has been completed in collaboration with the Department of Energy and Oak Ridge National Laboratory [5]. The development of evacuated microsphere insulation panels for cryogenic piping systems is being performed in collaboration with Technology Applications Inc. (Boulder, Colorado USA). Another project with AMAC International (Newport News, Virginia USA) is the development of a cryogenic transfer line with magnetic suspension.

5 CONCLUSION

A new pipeline test apparatus and method has been successfully implemented for the thermal performance testing of cryogenic piping systems. The apparatus was used, with the static liquid nitrogen evaporation method, to obtain accurate heat leakage rate data for full-scale cryogenic pipelines under actual field conditions. Example test data for three 18-meter-long pipelines (polyurethane foam, VJ/MLI with bayonets, and VJ/MLI with field joints) were given to describe the method of operation. The testing method lends itself to the development of a standardized heat transfer test for low-temperature piping systems. The method may also be extended to refrigeration and medium temperature applications from about 230 K to 373 K.

Current work at the Cryogenics Test Laboratory of NASA Kennedy Space Center includes the testing of a number a rigid and flexible cryogenic pipelines that include new technology thermal insulation materials. Fundamental to our applied research work are energy efficient transfer lines and low-temperature refrigeration systems for space launch sites and the supporting industrial infrastructure.

NOMENCLATURE

HTS	high temperature superconductivity
VJ/MLI	vacuum-jacketed multilayer insulation
k_{oafi}	overall thermal conductivity in actual field installations
CB_S	upstream cold box
CB_N	downstream cold box
CVP	cold vacuum pressure
WBT	warm boundary temperature
CBT	cold boundary temperature

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